Investigating the Structure of Coronal Mass Ejection Models with Galactic Cosmic Rays

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Aims:

- Model a two-step decrease in the GCR flux, in response to realistic 3-D CME field geometries.
- Increase understanding of the relation between energetic particle observations and CME structure.

Galactic Cosmic Rays and Forbush Decreases

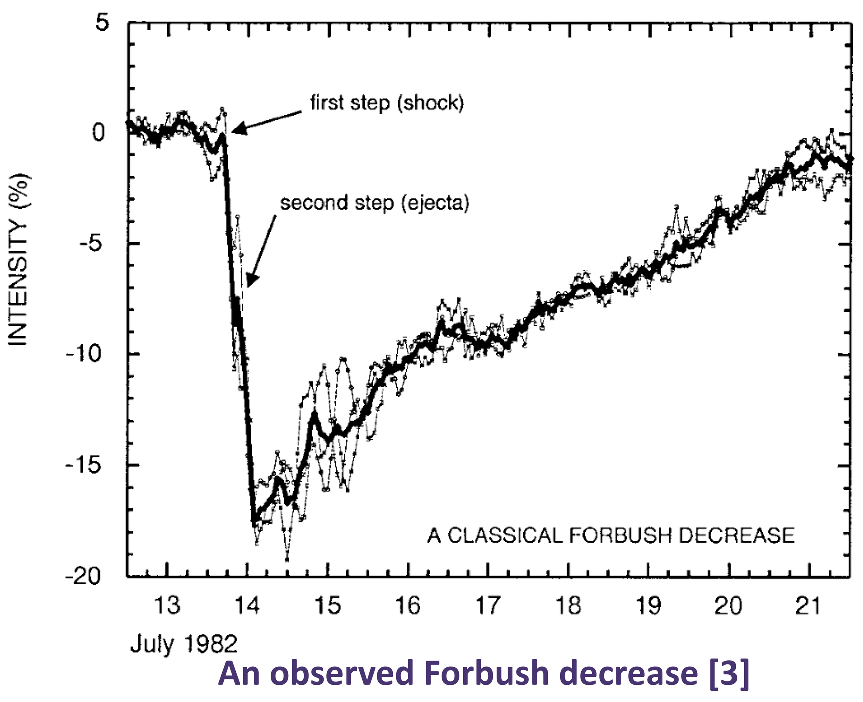
GCRs are **charged particles with extremely high energies** originating from outside the heliosphere. Transport theoretically described using Parker equation [1]: 3 terms represent advection, diffusion and drifts, and adiabatic cooling:

$$\frac{\partial f}{\partial t} + \boldsymbol{V}\cdot\nabla f - \nabla\cdot(\boldsymbol{K}\cdot\nabla f) - \frac{1}{3}(\nabla\cdot\boldsymbol{V})\frac{\partial f}{\partial \ln p} = 0$$

- Less good for modelling complicated transient structures: realistic magnetic fields would be hard to capture in a diffusion tensor.

Short term decreases in GCR flux caused by CMEs and SIRs called a **Forbush decrease** [2].

Fds have **varied** profiles: **2-step decrease** corresponding to the **sheath region** and the **magnetic cloud** structure of the CME.



An observed Forbush decrease [3]

3D Coronal Mass Ejection Models

CME magnetic structure (seen in in-situ measurements): a collisionless shock, a turbulent sheath region and a smoothly rotating magnetic field (flux rope) [4].

3DCORE Flux Rope:

- Gold-Hoyle Flux rope.
- Provides parameter fits based on event data.
- Accounts for a constant solar wind speed and expands self-similarly.
- No shock, sheath or CME wake.
- Analytic magnetic field model [8].

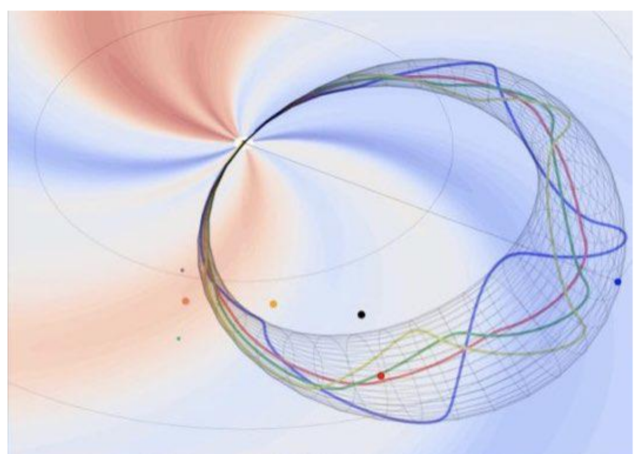
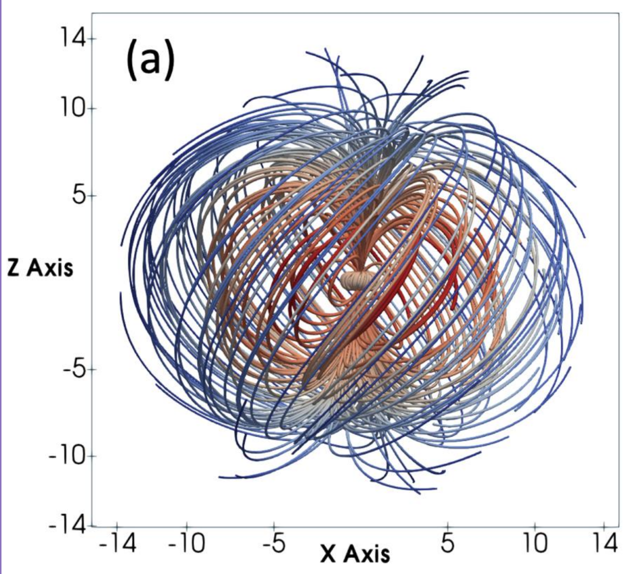


Image of 3DCORE flux rope model [9]



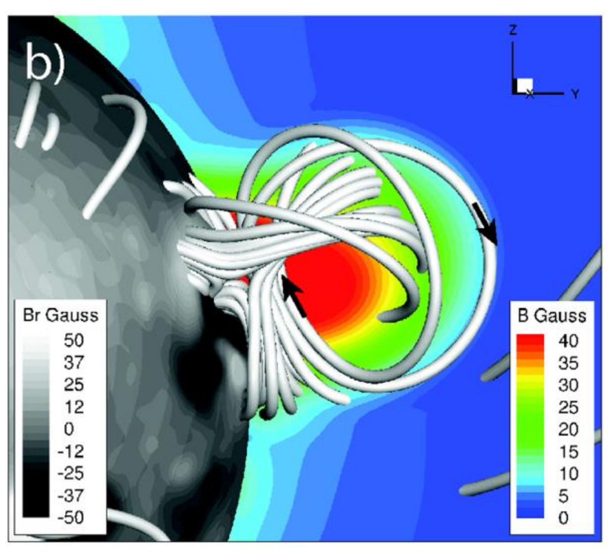
Magnetic field lines of a spheromak [7]

Spheromak CME:

- Spherical, ideal MHD simulation [5,6].
- Currently parker spiral SW.
- Inject toroidal spheromak model with given parameters and evolve.
- Spheromak reproduces smooth rotation of MC field in most places.
- Produces a magnetic field with shock, sheath region and magnetic cloud.

Gibson-Low Flux Rope:

- SWIFT MHD simulation from solar surface [10].
- Solar wind conditions from ADAPT magnetograms for idealised or real events.
- GL flux rope erupted from the solar surface into the heliosphere.
- Runs in real time at GFZ Potsdam but high-res "science" runs available.

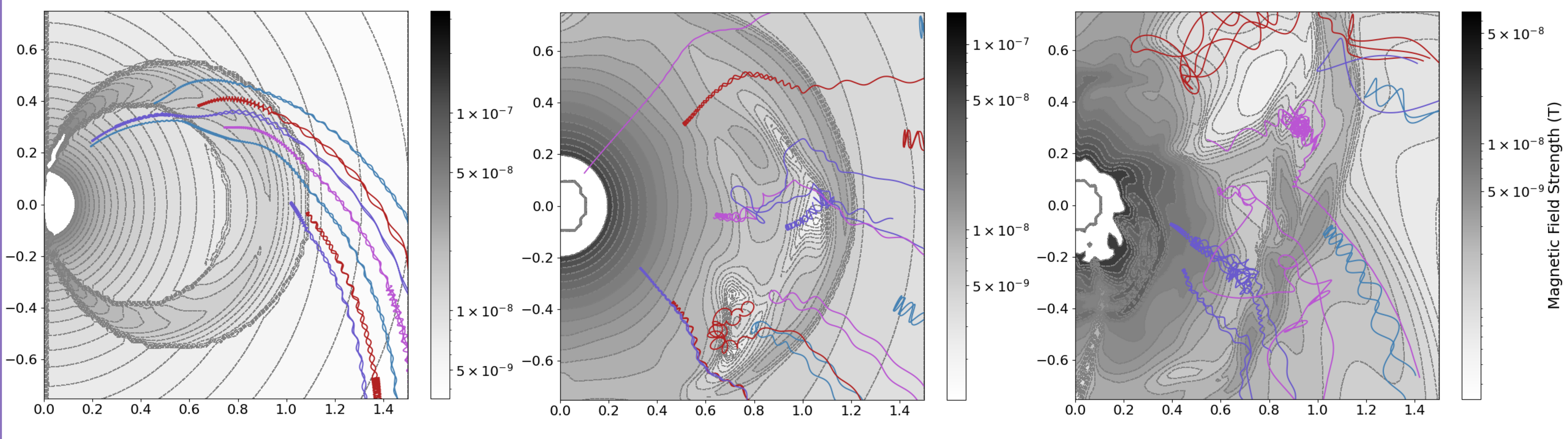


Gibson-Low FR simulated in AWSoM-R [11].

Modelling a Forbush Decrease

We use **full-orbit test particle simulations** of protons on top of interpolated output magnetic and electric fields from CME models to capture drifts, solar wind transport and energy changes**, in addition to gyroradius scale** effects (important near shocks, current sheets, etc.).

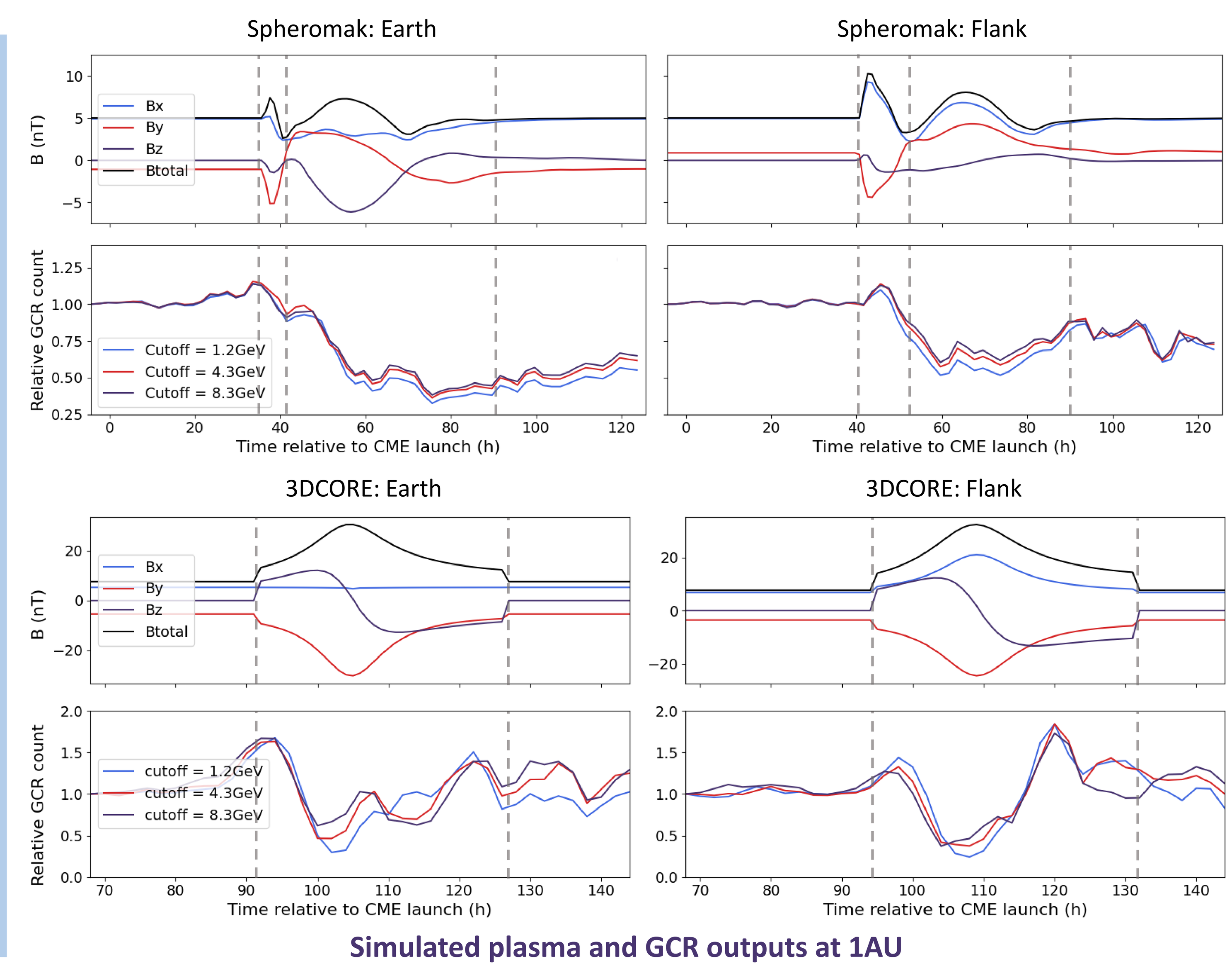
- Particles assigned a weight based from Badhwar-O'Niell model (solves radial PTE) [12].
- Isotropic input distribution initialised at radial boundaries and evolved in the stationary magnetic field.
- Output weights added together to form a distribution function after particles are evolved.



Plane plot (Z=0AU) of magnetic field strength of CMEs modelled using (left) analytic flux rope, (centre) MHD spheromak, and (right) MHD Gibson Low flux rope. Superimposed are the particle paths of 1-7 GeV protons

Results

- **GCR flux depends strongly on position within CME**: Magnetic field is weaker on one side, allows particles to enter and be trapped more easily.
- **Observed features replicated: 2-step decrease**, increase before shock.
- **Analytic model does not allow particles to efficiently access the inner flux rope** – need irregularities in MHD simulations.



Simulated plasma and GCR outputs at 1AU

A Pitch-Angle Scattering Problem?

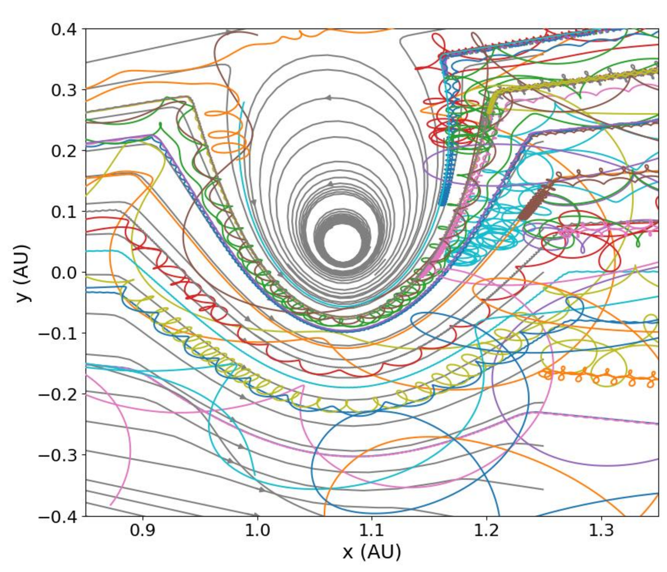
In order to reproduce GCR gradients over large distances, particles must undergo diffusion. Also, we **cannot replicate observed decrease magnitudes in FDs in model without pitch angle scattering.** Options for implementing in test-particle code:

Velocity isotropisation:

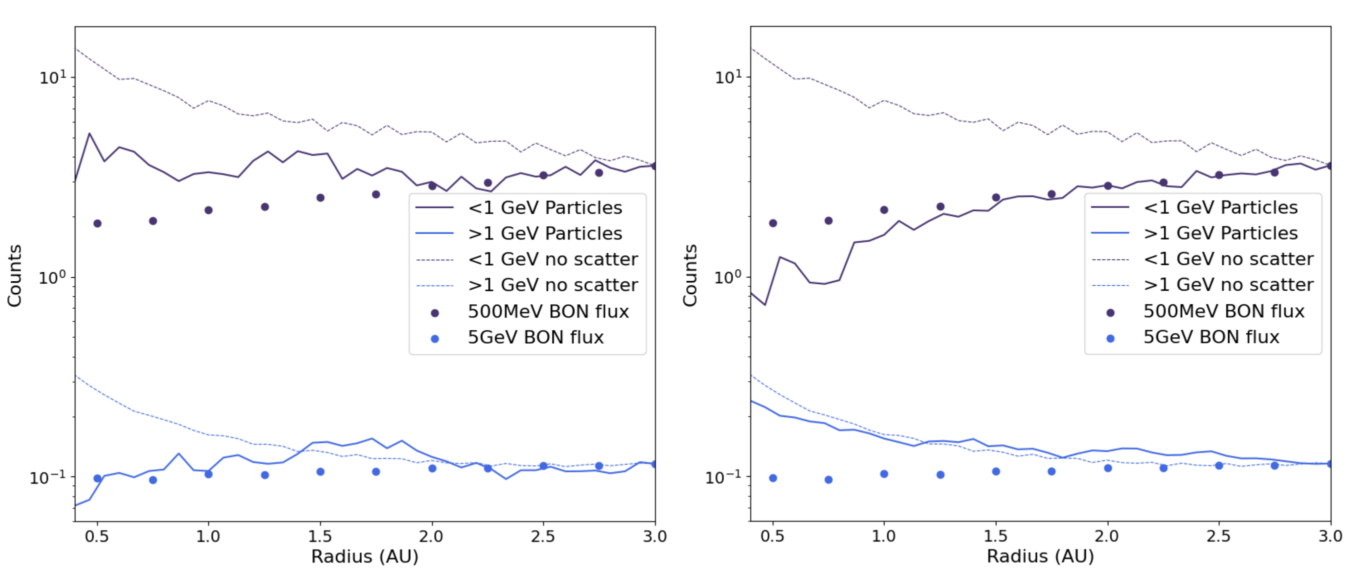
- Mean free path calculated from diffusion coefficient and velocity randomised every mfp
- Not physical as velocity changes instantaneously

Electromagnetic field scattering:

- Add fluctuating $\delta B/B_0$ to magnetic fields, causing pitch angle scattering.
- Requires correct parameterisation to reproduce radial gradient.



Without scattering, particles cannot enter closed magnetic field inside flux rope.



Particle radial intensities with scattering from (left) velocity isotropisation, (right) magnetic field fluctuations compared with BON model

[1] E.N. Parker, The passage of energetic charged particles through interplanetary space, Planetary and Space Science, Volume 13, Issue 1 (1965), [2] S. E. Forbush Phys. Rev. 51, 1108 (1937), [3] Cane, H.V. Coronal Mass Ejections and Forbush Decreases. Space Science Reviews 93, 55–77 (2000). [4] Burlaga, L., Sittler, E., Mariani, F., & Schwenn, R. 1981, JGR, 86, 6673, [5] A. Mignone et al 2007 ApJS 170 228,[6] Desai, R.T. et al. Three-Dimensional Simulations of Solar Wind Preconditioning and the 23 July 2012 Interplanetary Coronal Mass Ejection. Sol Phys 295, 130 (2020), [7] G. J. Koehn et al 2022 ApJ 941 139. [8] Andreas J. Weiss et al 2021 ApJS 252 9 [9] https://helioforecast.space/. [10] Arber et al., https://www.spacepager.eu/ [11] W B Manchester IV et al 2014 Plasma Phys. Control. Fusion 56 064006. [12] Slaba, T. C., and Whitman, K. The Badhwar-O'Neill 2020 GCR Model. Space Weather 18.6 (2020)

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